A-356 TYPE ALUMINUM CAST ALLOY, PART II
EFFECT OF BERYLLIUM CONCENTRATION

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(6) A-356 TYPE ALUMINUM CAST ALLOY, PART II: EFFECT OF BERYLLIUM CONCENTRATION,

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ABSTRACT

This investigation was conducted to determine the effect of variations of beryllium content on the mechanical properties and part strengths of "high purity" 356-T6 type aluminum alloys. Results are reported that were obtained from a series of similar "Tee" - shaped test castings, poured by two foundries in both sand and permanent mold, using metal of six different compositions. The "Tee's" of all chemistries were solution heat treated similarly and were aged for various times at two temperatures.

Both in sand castings and in chilled castings, at any aging temperature or time used experimentally, ultimate strength and yield strength increased from five to ten percent with a 0.20 weight percent increase in beryllium concentration. Elongation was not affected by beryllium additions. Part strength, as tested in bending, was increased by this increase in beryllium content approximately five percent when aluminum chills were used, three percent when iron chills were used and ten percent when unchilled.

I. INTRODUCTION

The majority of high strength, high integrity, light metal alloy castings are currently poured in a multiplicity of chemical combinations within a relatively restricted analytical range of the aluminum-silicon-magnesium system. These numerous 356-360 type aluminum alloys differ from each other only in the independent amounts of silicon, magnesium and beryllium present and in the level of iron impurity permitted. The mechanical properties of each of these alloys have been described. The strength data reported, however, are usually for a single, specific chemistry. They are usually obtained from dissected segments of a given production casting, repetitively poured by one foundry.[1] Such data are not directly comparative with the published values for other similar alloys, poured in other configurations and produced by other foundry sources. The available data have not demonstrated the individual and collective effect of the four chemical variables on relative alloy strength. The present study is an exploration of the effects of each of these variables.

The current chemical limits of this family of alloys are relatively narrow. The specified ranges of allowables vary by weight percent from 6.5 to 10.0 for silicon, from 0.2 to 0.7 for magnesium, from 0.0 to 0.30 for beryllium and maxima for iron varying between 0.20 and 0.5. Of these variables, the effect of magnesium concentration on the relative strength of the present 356-T6 type aluminum alloy series has been previously reported [2]. The chemical effect of silicon has also been studied and was determined to be negligible, at least within the prescribed compositional range [3]. It remained, then, to explore the influence of beryllium and iron on this alloy system.

I. INTRODUCTION (Cont'd.)

I.I Effect of Contamination

The deleterious effect of iron and other minor alloying constituents on the ductility of the aluminum-silicon-magnesium system has been recognized on a theoretical [4] and a practical[5] basis since the time 356 aluminum alloy was first suggested as a potential casting material[6]. Iron, as shown in Figure I, occurs as an impurity in the form of thin, often acicular, beta iron-silicon intermetallic compounds. These embrittle cast structure in proportion to the amount present [7]. It was the recognition of this fact that led the Aluminum Company of America, in 1954, to the announcement of XA356 as an experimental alloy[8]. This material was identical in nominal composition to 356 but with a reduction of the maximum permissible level of impurities. The reduction of iron concentration from 0.5 weight percent maximum to 0.2 weight percent maximum resulted in more ductile castings. This added ductility could be utilized by permitting increased aging times and/or temperatures to provide higher ultimate and yield strengths while maintaining adequate elongation. The aluminum alloy XA356 was immediately followed by the market introduction of A356, HP356 and X357[9], all "high purity" alloys.

I.2 Beryllium Additions

Apparently concurrent with developmental work on "high purity" 356[10], Cron and Zeuch of North American Aviation approached the problem of iron embrittlement with an attempt to chemically complex the iron rather than to remove it from the alloy. Early in 1956, a North American Materials Specification was issued describing a material, called initially 42B, and patented later as Tens-50[11]. The alloy, nominally 8.0 weight percent silicon, 0.5 weight percent magnesium, contained a 0.15 to 0.30

1.2 Beryllium Additions

weight percent beryllium addition which "helps control embrittlement by modification of the iron needles" to probably Al-Be-Fe-Si-Al_5-Si and Be-Fe-Si-Al_5[12]. A photomicrograph illustrating this reported modification is shown as Figure 2. A 0.4 weight percent maximum permissible iron level was specified for this alloy.

Using the principle of iron modification by beryllium, but coupling it with the use of high purity alloying materials, Precision Castings of Costa Mesa, California, formally announced in 1957 a material designated as 356CMB[13]. This material, properly cast and heat treated, showed a marked advantage over any competing alloy in the mechanical properties of heavily chilled castings[14].

Since this time, it has become increasingly common foundry practice to make arbitrary beryllium additions to the 356 type aluminum alloys in order to enhance mechanical properties, and inhibit magnesium loss during melting. Due to the expense of the element and the 0.05 weight percent maximum impurity limit imposed by many specifications, this beryllium addition is usually small.

1.3 Test Configuration

The relative effect of small compositional variations in beryllium on 356 type aluminum alloy strength could best be studied, not in separately cast test bars where minor strength differences between alloys might be masked by rapid cooling and ideal gating, but in a structural configuration of as much complexity as is economically feasible. A series of such castings could be reproducibly poured by a fixed foundry technique using metal of known, variable compositions. Such parts, after comparable heat

1.3 Test Configuration

treatment, can be statically loaded to failure under controlled conditions. Numerical test values so derived should be definitive. By studying the relative functional strength of a given configuration in its entirety, the various alloy compositions can be compared directly. These part strength data should be far more valid than are the mechanical property results generally obtained in alloy and heat treat studies which make use of separately cast test bars. In addition to part strength information, such a configuration could also supply standard mechanical property values derived from coupons machined from dissected segments of the failed castings.

The "Tee" bar casting, pictured in Figure 3, is one of two test configurations currently used by Douglas in foundry and alloy evaluations[3] [14]. While the configuration is uncored, and suggests little necessity to vary gating and chilling techniques, it does permit a strength evaluation not only of coupons cut from the casting but of the parent casting itself. The casting is poured and heat treated as an "H". The "H" is then bisected across the center arm into two identical "Tee"-shaped pieces. Each of these "Tee's" is individually placed in a jig and bend loaded to failure in a standard tensile testing machine. See Figure 4. The load is applied to the cantilever at the position shown in Figure 5.

The present report describes strength data obtained from a series of such castings produced by two foundries in 356 type aluminum alloys of varying beryllium concentrations.

2. EXPERIMENTAL PROCEDURES

2.1 Casting Production

Two foundries were requested to pour "Tee" bar castings in six 356 type aluminum alloys of varying beryllium concentration. The targets were 0.00, 0.04, 0.08, 0.12, 0.16, and 0.20 beryllium by weight percent. Silicon was to be maintained constant at 7.0 weight percent and magnesium held at 0.60 weight percent. Sodium modification was not permitted. Titanium, while held within the standard specification maximum of 0.20 weight percent, was left to foundry option.

At both foundries, each of the six target chemistries was produced as an individual melt. Eight "H" castings were made from each melt. As shown in Figure 3, each of these castings was poured so that only one end of the "H" was chilled. Each individual "H" thus produced, represented two interconnected, similarily gated parts - an essentially permanent mold cast "Tee", cooled at a maximal rate, and a sand cast "Tee", cooled at a minimal rate. The chills used by Foundry A were aluminum; those used by Foundry B were iron. Figure 6 illustrates the gating technique used.

Pouring temperatures were approximately 1375°F (745°C). All melts at Foundry B were degassed by nitrogen fluxing. Foundry A used both nitrogen and chlorine. A cover flux was used by Foundry B but not by Foundry A.

2.2 Heat Treatment

Castings produced by each foundry were heat treated by the foundry to identical schedules. Castings of each of the six target chemistries were solution heat treated in a single furnace load for twelve hours at 1010 ± 5°F (543 ± 2°C) and were quenched immediately in 140°F (60°C) water. Less than a five second time delay existed between the opening of the furnace door and the entrance of the castings into the water.

2.2 Heat Treatment

As has been suggested elsewhere[15], a twenty-four hour room temperature age interval was scheduled between the quenching and artificial aging of the castings. The use of this holding period does not imply agreement with the popular concept of its beneficial effect on mechanical properties. The author has, as yet, been unable to duplicate the reported advantage[16]. The holding period was specified for two reasons - first, to eliminate a potential experimental variable and second, because such practice is currently common to many production foundries.

The eight "H"'s so solution heat treated were divided randomly into two groups of four. One group of four castings from each of the six target chemistries, 24 castings in all, were artifically aged in one furnace load for various times at 320°F (160°C); the remaining 24 castings were artifically aged in another furnace load for various times at 350°F (177°C). The schedule was as follows - each time and temperature being represented by an "H" casting of each alloy:

(a) age at 320 $\pm$ 5°F (160°C) for 3, 5, 7 and 14 hours

(b) age at 350 $\pm$ 5°F (177°C) for 2, 3, 4 and 10 hours

Castings were fixed in the aging load so that at the above times and temperatures a representative of each target chemistry could be simultaneously removed from the furnace. With this technique, the furnace door could be quickly closed and no appreciable heat loss occurred. Castings so removed were air cooled.

2.3 Inspection

2.3.1 Chemistry

Spectrographic chemical analyses for each target melt produced by each

2.3.1 Chemistry (Cont'd.)

foundry were made independently on specially prepared disc samples by the producing foundry. The analyses were also determined by Douglas on the same chemical sample discs as well as on tensile coupons later cut from the test castings. The averages of these analyses for each melt appear in Table I. In general, there was good agreement between the values obtained by Douglas and by the independent laboratories.

2.3.2 Fluorescent Penetrant Inspection

Each "H" casting was inspected by fluorescent penetrant. All were judged acceptable and no discernible quality difference existed between melts or between the production of either foundry.

2.3.3 Radiography

Radiographic examination demonstrated a very light shrinkage condition along the midline of the 0.5 inch thick section of the chilled end and a moderate level of gas porosity in the sand end of the "H" in all castings received. These minor discontinuities, equally common to each alloy produced, were judged "acceptable" by an independent inspection laboratory, and were considered to be typical of the minor heterogeneities encountered in normal production runs. The radiographic quality level of castings from both foundries were approximately equivalent.

2.4 Testing

As described in the introduction, each "H" produced was bisected into two "Tee" shaped pieces which were subsequently bend loaded to failure as shown in Figures 4 and 5. The cantilevers fractured cleanly at the juncture of the two arms.

2.4 Testing (Cont'd.)

As shown in Figure 5, two tensile coupons were machined from each of the broken "Tee's." (Standard, flat, 0.2 inch thick sub-size from the material produced by Foundry A and standard, cylindrical, 0.25 inch diameter sub-size from the material produced by Foundry B). One coupon was machined from the 1 x 1 x 4 inch post section and the other coupon machined from the edge of the 1.5 inch wide, 0.5 inch thick arm. The center of the gage length of this latter coupon was then two inches from the point of fracture of the original "Tee". These coupons were then tensile tested by standard technique at a loading rate of 1,200 pounds per minute. Elongations reported were measured by "fit-back" in a one inch gage length. The mechanical properties of a given sand cast or chill cast "Tee" representing a given chemistry, aging temperature and time were considered to be the arithmetical mean of the two tensile coupons taken from it. Douglas has shown that tensile results obtained from these standard flat coupons are essentially equivalent to results obtained from standard round coupons.

3. RESULTS

3.1 Part Strength Testing

The bending load to part failure results for each of the individual "Tee's" produced by both foundries in each of the six target chemistries are reported in Table II and Table III. Table II lists the part strength values obtained from "Tee's" aged from the T-4 condition for various times at 320°F (160°C) and Table III for those aged at 350°F (177°C). These results are summarized in Figure 7 for parts containing various amounts of beryllium and aged for various times at 320°F (160°C) and Figure 8 for similar parts aged for various times at 350°F (177°C). In these figures solid lines designate the strength range; the broken lines designate the average properties.

3.2 Tensile Testing

The mechanical property results obtained from each of the six alloys produced by each of the foundries are also reported in Tables II and III. Table II presents tensile strength values obtained from sand cast and chill cast "Tee's" aged from the solution heat treated condition at 320°F (160°C) and Table III for those aged at 350°F (177°C).

The effect of beryllium concentration on the mechanical properties of sand cast and chill cast 356 variant type aluminum alloys appear in Figures 9 through 12. On each of these Figures, one set of curves describes tensile tests made on material aged at a given temperature for the minimum time used experimentally; the other set of curves describes tests made on material aged for the maximum time used experimentally at that temperature. Tensile results from material aged for times between these two extremes fall within the curves drawn. Figure 9 shows results from chill cast material aged at 320°F (160°C). Figure 10 shows results from chill cast material aged at 350°F (177°C). Figure 11 shows results from sand cast material aged at 320°F (177°C). Figure 12 shows results from sand cast material aged at 350°F (177°C).

Figures 13 through 15 illustrate the effect of several aging times and temperatures on the mechanical properties of three 356-T6 type aluminum alloys of constant 0.60 weight percent magnesium but varying beryllium concentration. Material described by the curves shown in Figure 13 contains no beryllium; that described in Figure 14, 0.10 weight percent beryllium; that described in Figure 15, 0.22 weight percent beryllium. Aluminum chills were used to produce all permanent mold data shown in these figures.

3.3 Metallographic Examination

The sand cast and chill cast microstructures of each of the six compositions produced by both Foundry A and Foundry B were examined. Metallographic specimens for this examination were excised from the grip end of that tensile test bar which had been machined from the 0.5 inch thick, 1.5 inch wide section of the "Tee". These specimens were taken from that end of the tensile test bar which had been closest to the point of fracture of the "Tee" when the part in its entirety was static loaded to failure.

No microstructural differences appeared to be induced by variation in beryllium concentration. Nor were variations induced by aging times or temperatures in either sand cast or chill cast material. It was thought necessary then, only to show typical photomicrographs of cast 356 type material containing no beryllium and of material containing the maximum beryllium addition made by each foundry. Figure 16 shows sand cast material produced by both foundries, material from Foundry A containing 0.60 weight percent magnesium with both 0.00 and 0.22 weight percent beryllium, and material from Foundry B containing 0.52 weight percent magnesium with both 0.00 and 0.16 weight percent beryllium. Figure 17 shows permanent mold cast material produced by both foundries in the same compositions. The material shown in Figure 16 as sand cast by a given foundry in a given composition is represented in Figure 17 by material excised from the permanent mold end of the identical "H" casting. Aging times and temperatures, 3 hours at 350°F (177°C), are identical for all materials of which photomicrographs are shown.

4. DISCUSSION

Figure 16 shows the typical microstructure of sand cast 356-T6 aluminum alloys produced by both Foundry A and Foundry B. As can be seen, considerable difference in microstructure exists between the production of the individual foundrys. At all beryllium concentrations studied, the primary silicon particles observed in Foundry A sand castings were, in general, large, acicular and irregularly shaped; those in Foundry B castings were quite small and finely dispersed. Although both foundries were specifically requested not to sodium innoculate, the form and dispersion of the fine silicon crystals surrounding the aluminum solid solution dendrites seen in Foundry B sand castings is typical of sodium modified 356 type aluminum alloys.[17]

While the foundry reported that sodium was not used and its presence was not experimentally detectable by flame spectrophotometric techniques, it would appear from the metallographic evidence that the metal poured by Foundry B was modified in some manner. Excluding the possibility of foundry production and record error, it is conceivable that both foundries initially melted prime ingot already modified. Foundry B subsequently degassed with nitrogen. Such fluxing should not chemically alter the initial modification. Foundry A, however, fluxed with gaseous chlorine in addition to a nitrogen flux. Under these conditions, sodium certainly, and boron probably would be removed from the melt as chlorides. This difference in fluxing practice could explain the basic variation in sand cast 356 type aluminum alloy microstructure found between material supplied by the two sources.

The marked difference in silicon particle structure and dispersion

4. DISCUSSION (Cont'd.)

demonstrated between sand castings produced by Foundry A and those produced by Foundry B was not evident in the microstructure of the chilled castings respectively produced. See Figure 17. The effect of modification was apparently masked by rapid cooling from the molten state. The primary silicon shown in Figure 17 had insufficient time to grow to the sizes shown in Figure 16.

As would be expected, the dendrite cell size of the chill cast material shown in Figure 17, was, on the average, considerably smaller than that of the sand cast material shown in Figure 16. Note also in Figure 17 that the dendrite cells of the aluminum chill cast material produced by Foundry A appear to be somewhat smaller than those of similar material iron chill cast by Foundry B. If real, this size difference probably must also be ascribed to variation in cooling rate, and not to magnesium concentration. The same slight variation in microstructure between aluminum chilled and iron chilled parts has been previously shown to be independent of the minor changes in magnesium content within this family of alloys[2]. The variation apparently obtains regardless of beryllium concentration or aging schedule. It therefore must be attributed to the greater heat conductivity of the aluminum chills which was not compensated for by the greater mass of the iron chills used by Foundry B. Time for dendrite and constituent growth was limited by more rapid cooling.

The practical structural advantage of this more rapid chill is reflected by the consistently higher mechanical properties and part strengths shown in Tables II and III for aluminum chilled material. Although in general,

4. DISCUSSION (Cont'd.)

Foundry B produced parts containing less magnesium than did Foundry A, the data from two melts can be compared directly. Melt "R", Foundry A and Melt "S", Foundry B are of equivalent chemistry. Here, aluminum chilled material demonstrated, at both aging temperatures, an approximate ten percent advantage in ultimate, yield and part strength over iron chilled material.

Regardless of the differences in strength and in microstructure which exist between parts produced by each foundry, the castings produced by an individual foundry show similar trends. With silicon and magnesium held constant, at any given aging temperature or time used experimentally, ultimate strength and yield strength increase as a function of increase in beryllium concentration from 0.00 to approximately 0.20 weight percent. In both sand castings and chilled castings, this 0.2 weight percent beryllium addition produces approximately a five to ten percent increase in both tensile ultimate and tensile yield measured at 0.2 percent offset. Full benefit of the beryllium addition on tensile strength is apparently achieved at approximately 0.10 weight percent and concentrations beyond this point have no apparent effect. At least at the iron impurity levels (0.10 to 0.15 weight percent) used experimentally, beryllium additions appear to have slight, if any, effect on the ductility of chill cast material and none at all on the ductility of sand cast material. See Figures 9 through 12.

At a constant magnesium concentration, chill cast part strengths are increased approximately five percent and sand cast part strengths approximately ten percent by beryllium addition. Solely from the test

4. DISCUSSION (Cont'd.)

values presented, it would appear that the full benefit of beryllium might not be reached until additions are in excess of 0.15 weight percent. The discrepancy between this concentration and the lesser amount apparently required to produce maximum tensile strength (0.10 weight percent) can not be currently explained except on the basis of test scatter.

At any given heat treatment, regardless of chilling technique or of the beryllium concentration used experimentally, the mechanical properties of test coupons taken from chilled castings had approximately a 10 to 20 percent advantage over the equivalent sand casting. Tensile yield strengths for sand castings were, however, only slightly less than the values obtained from heavily chilled castings for the identical alloy and heat treatment-from zero to four percent. Elongations, as would be expected, were considerably less for sand castings as opposed to chilled castings.

As previously reported[3], the advantage of chill cast structure over sand cast structure of similar composition and heat treatment was considerably more pronounced when expressed as relative part strength. See Figures 7 and 8. Despite the essential similarity of sand cast and chill cast yield strengths obtained from coupons cut from the same "H" casting, the aluminum chilled halves showed a 35 to 55 percent (median 50 percent) part strength advantage over their sand cast counterparts. The more slowly cooled, iron chilled castings showed somewhat less of an advantage, from 17 to 33 percent (median 25 percent). The strength differential between a chill cast "Tee" and the corresponding sand cast "Tee" was not increased by beryllium addition. It was, however, somewhat influenced by aging temperature, 350°F (177°C) producing a greater

4. DISCUSSION (Cont'd.)

differential than did 320°F (160°C).

The greater relative advantage for chill cast part strength than for chill cast tensile strength when compared to similar sand cast material can be partially explained on the basis of the photomacrographs shown in Figures 18 and 19 . These figures show typical cross-sections of the juncture of the arm with the base of the "Tee". This is the point of fracture of the part under static load. The polished surfaces were heavily etched with five percent hydrofluoric acid. Figure 18, representing a typical sand cast cross section, shows dendrites of approximately constant size. These dendrites grew from the molten state under conditions more nearly approaching equilibrium than did the dendrites shown in Figure 19, a typical chill cast cross-section. In this latter figure, there is a considerable difference in the size of the dendrites ranging from relatively small at the periphery to relatively large at the center, or last cooled area. The "Tee" under bending load would be stressed in tension at the upper surface and in compression at the lower. The neutral axis would then run through the larger dendrites were microcompositional variations are greatest, shrinkage most severe and general strength presumably lowest. The chilled "Tee" is thus loaded in the areas of maximum strength. Tensile coupons, however, excised from this casting and machined on all sides, represent the matrix of the section, the larger dendrites and the zone of lesser strength. A hypothetical strength differential of this magnitude between part strength and tensile strength would not obtain in sand castings were the dendrites toward the periphery or skin are more nearly similar, in size and kind, to the dendrites of the matrix.

4. DISCUSSION (Cont'd.)

At all beryllium concentrations used experimentally, seven hours of aging at 320°F (160°C) was required to produce the strength levels achieved with similar T-4 material using two hours at 350°F (177°C) See Figures 13 through 15. It would also appear from these data that higher strength can be produced in 356-T6 variant type aluminum alloys using the 350°F (160°C) age. Ductility, of course is somewhat less at the higher aging temperature.

It appears that beryllium might perform two functions in this alloy system. Its first and probably most significant effect is that of a second deoxidizer. This results in a cleaner melt with relatively more magnesium available for the formation of Mg_2 Si, the principle hardening agent. Any excess beryllium then acts, in a minor way, as a dispersion hardener. Such a hypothesis readily explains the variation in the apparent quantity of beryllium (0.10 to 0.15 weight percent) needed to achieve the maximum mechanical property increases ascribable to this alloying addition.

5. CONCLUSIONS

1. With silicon and magnesium concentration held constant, at any given aging temperature or time used experimentally, the tensile ultimate and tensile yield strengths of castings increase from five to ten percent with a 0.20 weight percent increase in beryllium concentration. Full benefit of this alloying addition on tensile

5. CONCLUSIONS (Cont'd.)

strength is apparently achieved at approximately 0.10 weight percent beryllium.

2. At least at the iron impurity levels used experimentally, up to 0.20 weight percent beryllium additions have little or no effect on the ductility of cast 356-T6 type aluminum alloys.

3. Chill cast part strength, when aluminum chills were used, was increased approximately five percent by up to a 0.20 weight percent increase in beryllium concentration and approximately three percent when iron chills were used.

4. Sand cast part strength was increased approximately ten percent by up to 0.20 weight percent beryllium addition.

5. The beryllium concentration required to produce maximum benefit on part strength is apparently in excess of 0.10 weight percent.

6. At any given heat treatment, regardless of the chilling technique or of the beryllium concentration used experimentally, the mechanical properties of test coupons taken from chilled castings had approximately a 10 to 20 percent advantage over the equivalent sand casting.

7. Tensile yield strengths for sand castings were only slightly less than the values obtained from heavily chilled castings for the identical alloy and heat treatment. Elongations, however, were markedly less for sand castings.

5. CONCLUSIONS (Cont'd.)

8. Aluminum chilled castings, at all beryllium concentrations used experimentally, showed a 35 to 55 percent part strength advantage over their sand cast counterparts. The more slowly cooled iron chilled castings showed a 17 to 33 percent advantage over the sand castings of similar aging schedule and chemical composition.

9. Aging for seven hours at 320°F (160°C) produces strength levels approximately equivalent to those achieved with chemically similar T-4 material aged for two hours at 350°F (177°C).

10. Higher strength levels in all 356-T6 variant type aluminum alloys can be produced using the 350°F (177°C) aging temperature although ductility is slightly impaired.

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DATA:

Filed under Laboratory Work Sheet No. 33675
PCR Book 17347, page 13
PCR Book 17748, pages 13-15, 21-50

EWO 52704
SO 80305-300
JWO 0001

TABLE I

CHEMICAL COMPOSITION *

(Weight Percent)

MELT	FOUNDRY	MAGNESIUM	SILICON	IRON	TITANIUM	BERYLLIUM	ALUMINUM ***
C	A	0.59 (0.60)**	7.0 (7.00)**	0.15	0.16	NIL	Balance
Q	A	0.59 (0.60)	6.8 (7.00)	0.16	0.16	0.06(0.04)**	Balance
R	A	0.59 (0.60)	7.0 (7.00)	0.15	0.15	0.10(0.08)	Balance
S	A	0.59 (0.60)	7.0 (7.00)	0.15	0.15	0.13(0.12)	Balance
T	A	0.59 (0.60)	6.8 (7.00)	0.15	0.15	0.18(0.16)	Balance
U	A	0.60 (0.60)	6.9 (7.00)	0.15	0.15	0.22(0.20)	Balance
C	B	0.54 (0.60)	7.0 (7.00)	0.10	0.15	NIL	Balance
Q	B	0.51 (0.60)	7.1 (7.00)	0.10	0.16	0.05 (0.04)	Balance
R	B	0.51 (0.60)	7.1 (7.00)	0.11	0.16	0.06 (0.08)	Balance
S	B	0.58 (0.60)	7.0 (7.00)	0.10	0.14	0.10 (0.12)	Balance
T	B	0.50 (0.60)	6.9 (7.00)	0.10	0.16	0.14 (0.16)	Balance
U	B	0.52 (0.60)	7.0 (7.00)	0.10	0.15	0.16 (0.20)	Balance

* Chemistries reported are the average of three analyses made by Douglas and the supplier.
** Target chemistry in parentheses
*** Including minor impurities

TABLE II

EFFECT OF AGING TIME ON THE STRENGTH OF CAST BERYLLIUM-CONTAINING 356-

(TENSILE VALUES REPORTED ARE THE AVERAG

Me	Foundry	Chilling Technique	Magnesium Content by Weight Percent	Beryllium Content by Weight Percent	3 Hours				5 H	
					Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI)	Fty (KSI)
C	A	Aluminum	0.59	NIL	48.4	34.4	10.0	1244	50.2	39.5
C	B	Iron	0.54	NIL	43.3	26.6	18.5	1058	45.0	31.0
Q	A	Aluminum	0.59	0.06	50.6	36.5	12.5	1295	54.1	40.5
Q	B	Iron	0.51	0.05	46.0	29.5	15.0	1052	49.0	33.6
R	A	Aluminum	0.59	0.10	53.0	36.0	16.0	1313	53.5	39.7
R	B	Iron	0.51	0.06	46.1	29.8	14.0	998	48.0	32.5
S	A	Aluminum	0.59	0.13	51.8	36.0	14.0	1313	54.0	40.2
S	B	Iron	0.58	0.10	46.2	30.3	11.0	1148	49.4	32.5
T	A	Aluminum	0.59	0.18	52.0	37.1	11.0	1336	54.7	41.2
T	B	Iron	0.50	0.14	48.0	32.0	16.5	1088	50.0	33.0
U	A	Aluminum	0.60	0.22	52.3	37.2	11.0	1350	54.8	41.4
U	B	Iron	0.52	0.16	47.0	30.9	12.5	1148	47.2	33.2
C	A	Sand	0.59	NIL	41.9	34.2	3.0	971	42.7	37.8
C	B	Sand	0.54	NIL	36.5	26.6	4.5	854	38.4	29.9
Q	A	Sand	0.59	0.06	43.0	35.2	3.0	952	44.8	38.3
Q	B	Sand	0.51	0.05	38.8	30.2	3.0	890	39.0	31.5
R	A	Sand	0.59	0.10	44.2	34.2	4.0	948	45.1	37.7
R	B	Sand	0.51	0.06	38.1	28.4	4.0	870	40.2	31.1
S	A	Sand	0.59	0.13	39.1	32.7	2.0	867	42.0	36.3
S	B	Sand	0.58	0.10	40.0	30.0	4.5	980	42.1	31.6
T	A	Sand	0.59	0.18	41.4	33.5	2.5	992	45.4	38.5
T	B	Sand	0.50	0.14	40.3	30.6	4.0	1060	39.7	31.6
U	A	Sand	0.60	0.22	44.0	35.2	4.0	972	46.8	39.1
U	B	Sand	0.52	0.16	38.5	29.3	3.5	1010	41.0	32.8

TABLE 11

·CONTAINING 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 AT 320°F (160°C)

:D ARE THE AVERAGE OF TWO TESTS)

	5 Hours				7 Hours				14 Hours			
to re ds)	Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)
44	50.2	39.5	9.0	1296	52.7	41.9	13.0	1376	53.8	44.7	10.5	1328
58	45.0	31.0	11.5	1150	47.0	33.0	15.5	1150	48.4	42.0	9.0	1278
95	54.1	40.5	10.5	1317	55.3	43.5	10.0	1407	54.6	44.7	6.0	1427
52	49.0	33.6	15.0	1164	49.0	35.5	14.5	1168	52.2	40.4	11.5	1200
13	53.5	39.7	9.0	1370	56.3	43.3	13.0	1367	58.0	47.7	9.0	1480
98	48.0	32.5	12.5	1184	48.6	34.3	12.5	1134	50.5	38.4	9.5	1102
13	54.0	40.2	13.0	1405	55.2	43.8	9.5	1364	57.1	47.6	7.5	1485
48	49.4	32.5	11.0	1188	48.5	35.2	11.5	1290	50.7	39.1	9.0	1280
36	54.7	41.2	10.5	1343	55.1	42.8	9.0	1416	56.1	47.0	6.5	1374
88	50.0	33.0	12.5	1168	48.5	36.0	8.0	1344	51.8	40.2	6.0	1200
50	54.8	41.4	8.5	1371	54.2	43.4	8.0	1322	56.1	45.0	9.0	1439
48	47.2	33.2	8.5	1208	48.2	35.5	9.5	1348	51.9	39.8	11.5	1262
71	42.7	37.8	1.5	942	44.7	39.2	2.0	908	46.0	42.8	0.5	971
54	38.4	29.9	4.5	892	40.0	32.4	3.5	912	43.3	40.5	2.0	980
52	44.8	38.3	2.5	951	45.2	40.6	2.0	878	51.9	46.1	2.0	887
90	39.0	31.5	3.5	894	41.0	35.1	4.0	920	44.5	39.0	3.5	966
18	45.1	37.7	2.5	952	48.1	40.5	1.0	911	51.9	45.8	0.5	905
70	40.2	31.1	3.5	936	42.6	35.1	3.5	940	43.7	39.0	1.5	956
57	42.0	36.3	1.25	972	44.9	40.4	1.25	953	47.6	45.0	1.0	978
30	42.1	31.6	2.5	1004	42.7	34.8	3.0	1030	45.2	38.7	2.0	1030
12	45.4	38.5	2.0	1021	47.5	41.5	1.0	1033	50.1	45.4	0.5	1012
50	39.7	31.6	3.0	980	42.9	34.7	5.0	1020	44.0	38.4	2.5	1008
72	46.8	39.1	1.75	992	48.3	42.0	1.5	1049	51.2	44.0	1.0	1034
0	41.0	32.8	3.0	990	42.9	34.0	3.5	1090	43.5	37.1	2.0	1044

TABLE III

EFFECT OF AGING TIME ON THE STRENGTH OF CAST BERYLLIUM-CONTAINING 356

(TENSILE VALUES REPORTED ARE THE

Melt	Foundry	Chilling Technique	Magnesium Content by Weight Percent	Beryllium Content by Weight Percent	2 Hours				3	
					Ftu (KSI)	Fty (KSI)	Elong. Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI)	F (K
C	A	Aluminum	0.59	NIL	51.1	41.0	8.5	1372	53.0	4
C	B	Iron	0.54	NIL	47.5	35.8	10.5	1260	48.6	3
Q	A	Aluminum	0.59	0.06	55.3	39.9	13.0	1307	57.4	4
Q	B	Iron	0.51	0.05	50.7	37.0	14.0	1152	52.0	4
R	A	Aluminum	0.59	0.10	55.2	43.5	8.0	1442	56.0	4
R	B	Iron	0.51	0.06	47.9	35.4	9.0	1300	50.1	3
S	A	Aluminum	0.59	0.13	55.3	43.7	11.0	1380	56.5	4
S	B	Iron	0.58	0.10	49.9	37.4	11.0	1212	51.2	4
T	A	Aluminum	0.59	0.18	55.6	43.4	11.0	1391	55.8	4
T	B	Iron	0.50	0.14	50.0	37.3	10.0	1234	50.3	4
U	A	Aluminum	0.60	0.22	55.7	42.9	13.0	1447	55.8	4
U	B	Iron	0.52	0.16	50.1	36.7	13.0	1234	51.1	3
C	A	Sand	0.59	NIL	45.0	40.8	1.5	912	46.7	4
C	B	Sand	0.54	NIL	40.3	35.3	4.0	972	42.4	3
Q	A	Sand	0.59	0.06	46.7	40.1	2.0	936	48.6	4
Q	B	Sand	0.51	0.05	42.2	37.5	1.5	1024	43.7	3
R	A	Sand	0.59	0.10	46.8	41.4	2.5	923	49.9	4
R	B	Sand	0.51	0.06	42.5	35.5	2.5	946	44.5	3
S	A	Sand	0.59	0.13	44.4	40.5	1.0	873	46.3	4
S	B	Sand	0.58	0.10	43.4	36.6	3.5	1004	45.6	3
T	A	Sand	0.59	0.18	46.6	41.7	1.0	1084	48.7	4
T	B	Sand	0.50	0.14	44.0	36.0	4.0	1036	45.2	3
U	A	Sand	0.60	0.22	47.6	41.5	2.0	1000	48.3	4
U	B	Sand	0.52	0.16	44.5	34.3	2.0	1008	44.1	3

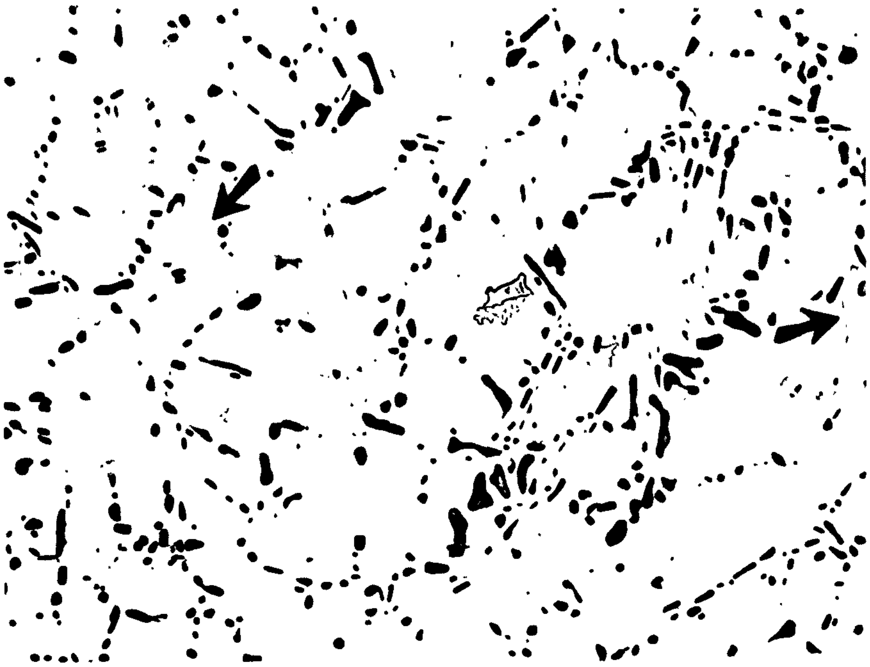
TABLE III

LIUM-CONTAINING 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 AT 350°F (177°C)

S REPORTED ARE THE AVERAGE OF TWO TESTS

	3 Hours				5 Hours				10 Hours			
oad to ailure Pounds)	Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)	Ftu (KSI)	Fty (KSI)	Elong, Percent (In 1")	Load to Failure (Pounds)
1372	53.0	43.8	10.5	1362	53.4	46.0	11.0	1437	53.8	46.3	6.0	1386
1260	48.6	38.0	13.5	1240	50.1	42.7	7.0	1314	50.0	43.4	8.0	1284
1307	57.4	47.3	9.0	1433	56.1	48.2	6.5	1391	56.2	49.9	5.5	1465
1152	52.0	40.8	11.0	1172	53.0	43.9	9.0	1204	53.3	46.5	7.0	1252
1442	56.0	47.3	6.0	1383	57.8	49.7	5.5	1442	57.8	51.3	8.0	1498
1300	50.1	39.2	9.0	1260	52.8	43.3	9.5	1155	52.6	44.8	7.5	1234
1380	56.5	46.6	9.0	1426	57.0	48.7	8.0	1433	56.8	50.4	5.5	1490
1212	51.2	41.4	7.0	1396	52.3	44.6	6.0	1392	52.9	46.2	3.5	1420
1391	55.8	45.2	8.5	1380	56.3	48.0	7.0	1407	56.6	50.4	8.0	1471
1234	50.3	40.1	12.0	1228	52.9	43.7	8.0	1332	53.2	45.6	5.0	1288
1447	55.8	45.6	9.0	1483	56.2	47.7	7.5	1482	56.0	48.8	6.25	1454
1234	51.1	39.3	11.5	1340	52.8	43.4	8.5	1274	52.9	45.1	6.0	1334
912	46.7	43.6	1.5	977	45.6	44.5	1.0	951	47.2	45.8	1.5	949
972	42.4	37.0	2.5	900	44.6	41.5	2.0	962	45.1	43.2	1.5	1020
936	48.6	44.4	1.5	913	49.9	47.1	2.0	825	50.6	48.0	1.0	888
1024	43.7	39.0	3.0	1040	47.0	42.5	2.5	970	48.3	42.0	1.0	948
923	49.9	45.1	1.25	1049	52.0	48.2	0.75	832	48.5	48.5	0.75	866
946	44.5	38.6	2.0	986	47.7	42.3	2.0	1072	48.1	44.4	1.25	966
873	46.3	44.0	1.0	869	46.5	45.7	0.0	875	47.1	46.2	0.5	907
1004	45.6	39.1	2.5	1100	49.2	42.1	2.0	1092	48.6	43.5	1.0	1020
1084	48.7	45.0	1.0	1028	49.5	45.8	0.5	992	49.9	48.0	0.5	971
1036	45.2	38.8	2.0	954	47.9	42.8	3.5	1108	47.0	42.2	2.5	972
1000	48.3	42.9	1.75	1001	51.5	46.9	1.75	1040	50.2	48.0	1.0	1071
1008	44.1	37.3	2.5	1092	45.9	40.7	2.0	970	48.3	43.2	2.0	1080

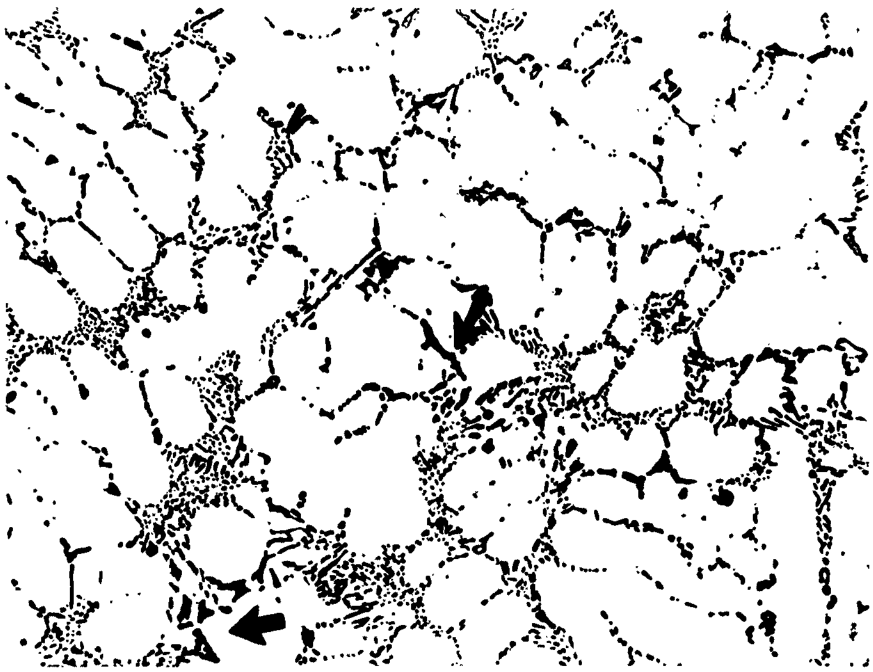
2



MAGN. 400X **FIGURE 1** M17230

SAND CAST 356-T6 ALUMINUM ALLOY CONTAINING APPROXIMATELY 0.3 WEIGHT PERCENT IRON

UNETCHED ARROWS INDICATE FE-SI INTERMETALLIC



MAGN. 100X **FIGURE 2** M14633

SAND CAST 356-T6 ALUMINUM ALLOY CONTAINING APPROXIMATELY 0.06 WEIGHT PERCENT BERYLLIUM

UNETCHED ARROWS INDICATE A BE-FE COMPLEX

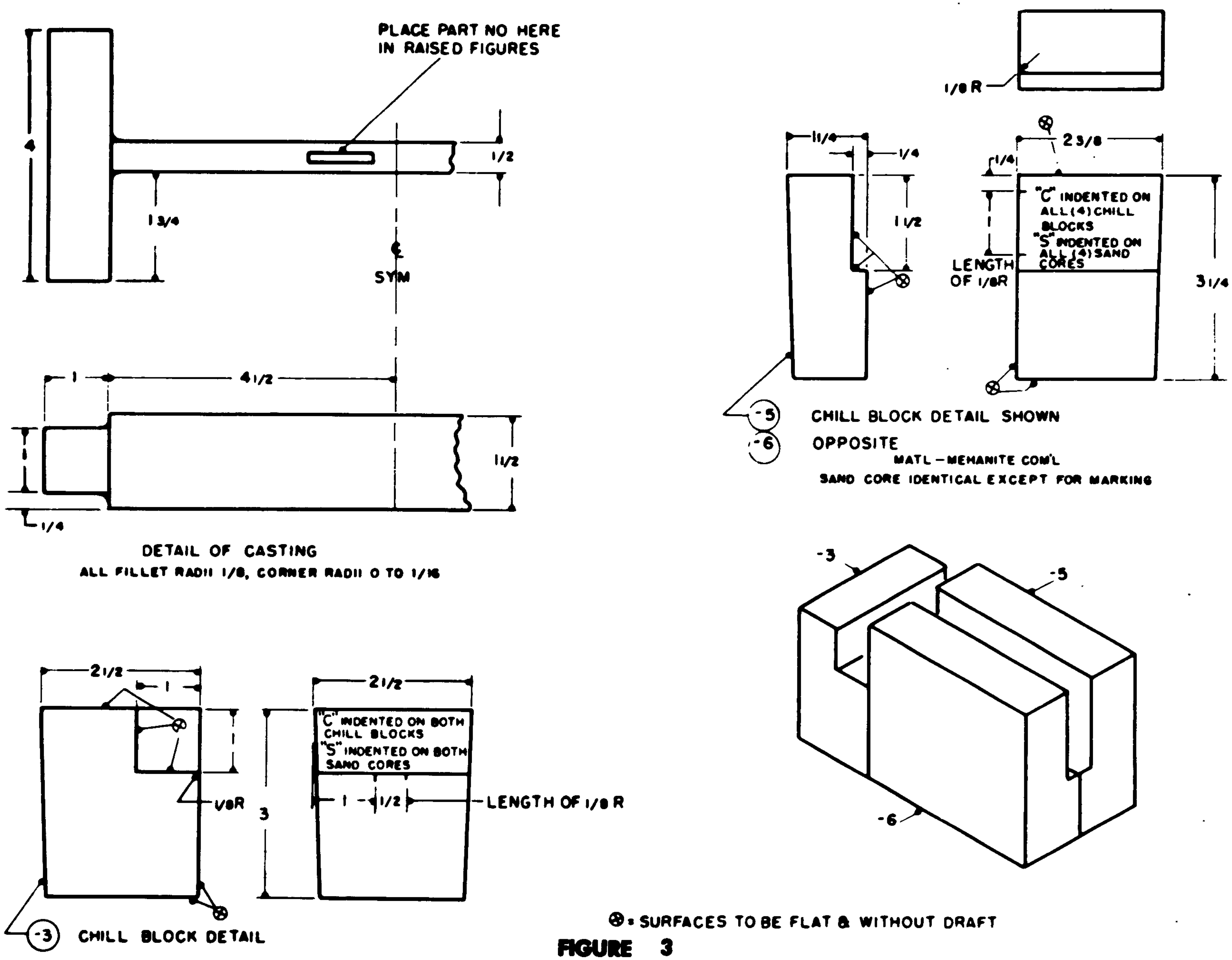
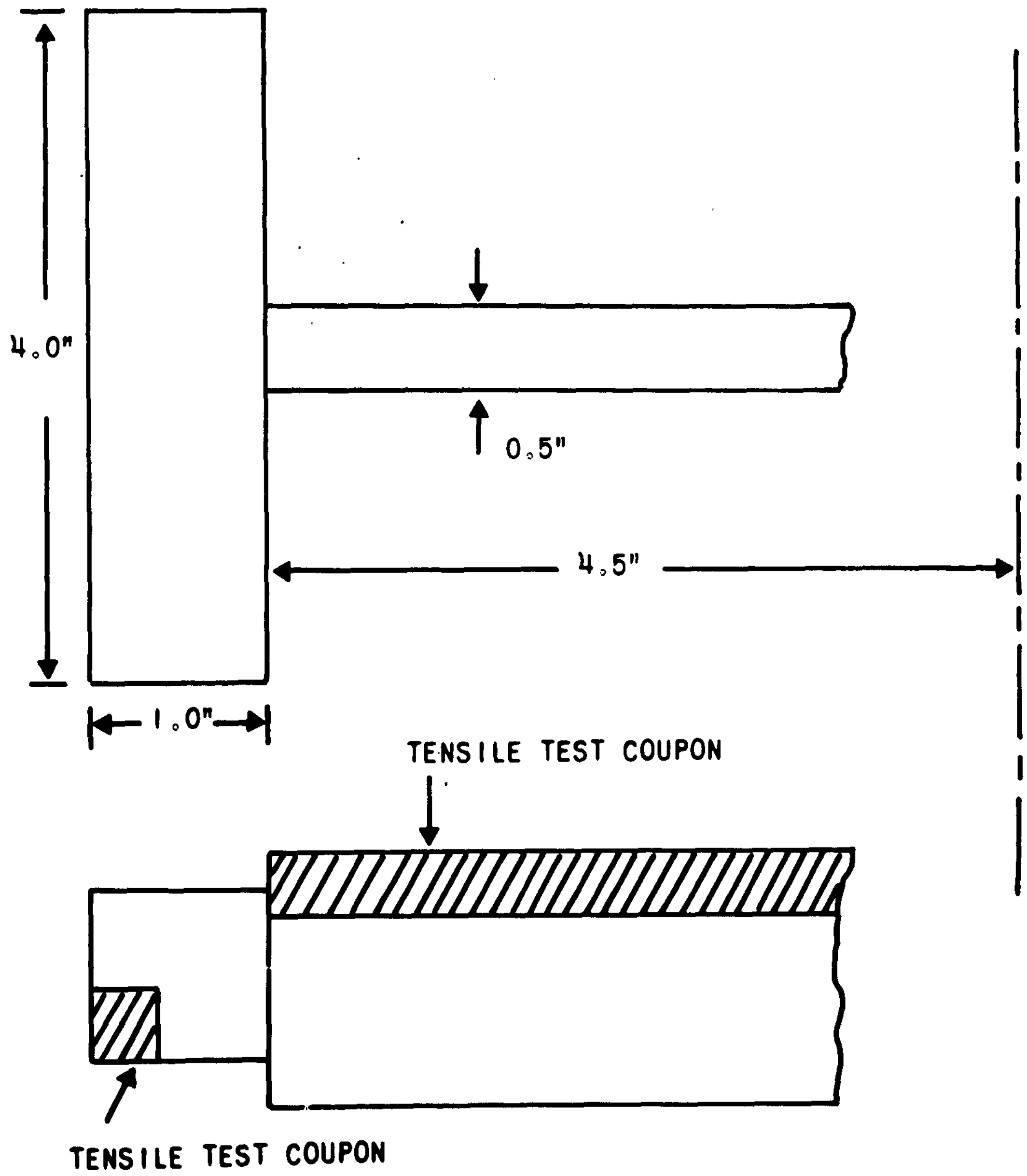


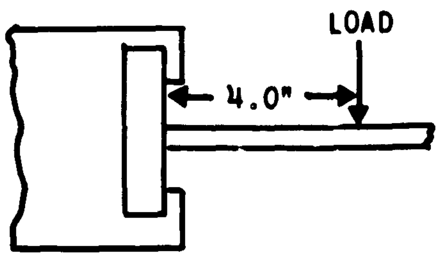
FIGURE 3
CASTING - STRUCTURAL EVALUATION TEST
(P/N 3838789)

FIGURE 4
TECHNIQUE USED FOR STATIC LOADING TO FAILURE "TEE" BAR CASTINGS

FIGURE 5

"TEE" BAR TEST CASTING AND TECHNIQUE USED IN BEND LOADING IT TO FAILURE





STATIC TEST ARRANGEMENT

MAGN. APPROXIMATELY 1/6X

FIGURE 6

GATING AND CHILLING TECHNIQUE USED FOR PRODUCTION OF "TEE" BARS

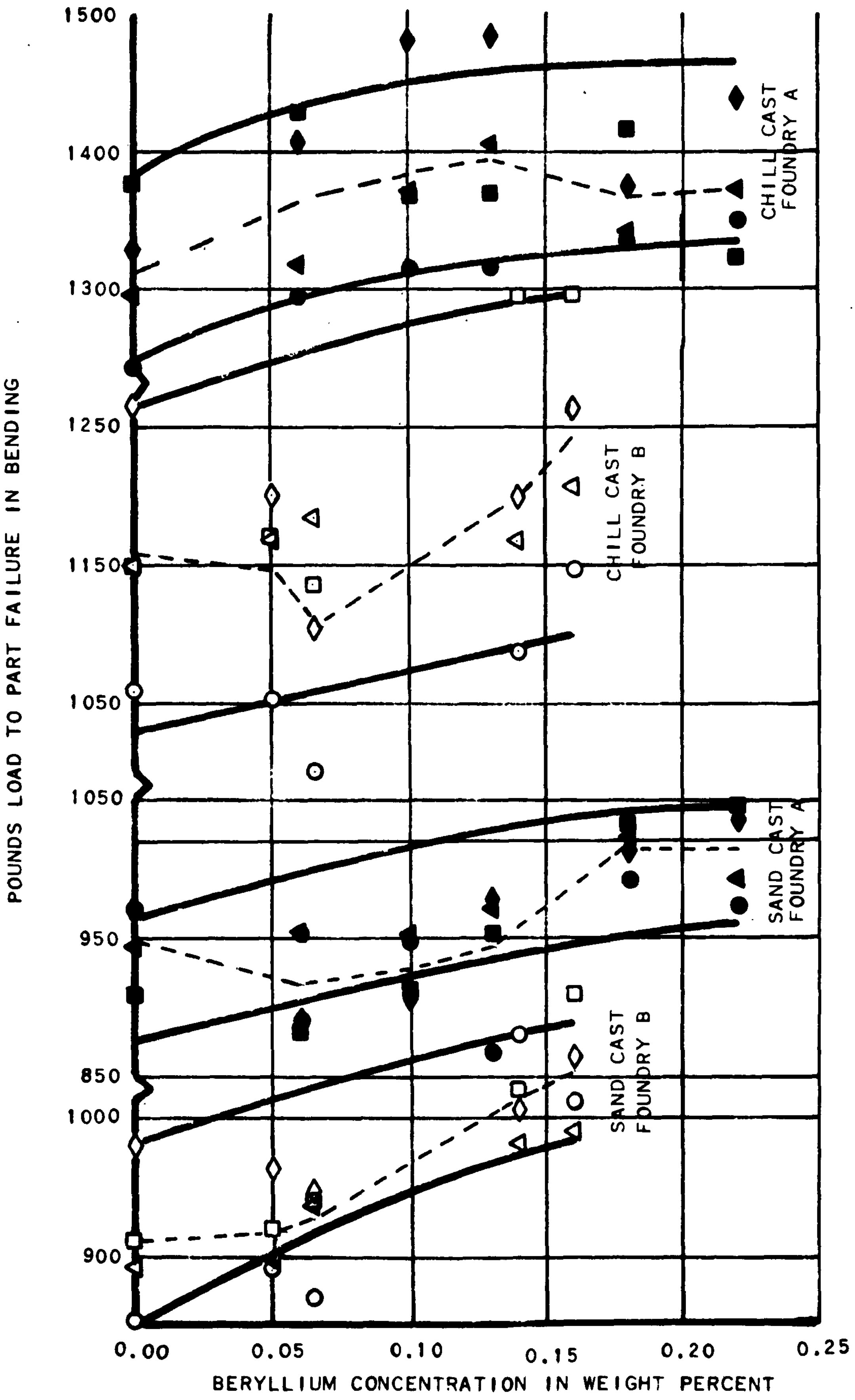


FIGURE 7

EFFECT OF BERYLLIUM CONCENTRATION ON THE PART STRENGTH OF 356-T6
TYPE ALUMINUM ALLOYS
(PARTS AGED AT 320° F)

- ● AGED 3 HOURS
- ◀ AGED 5 HOURS
- ■ AGED 7 HOURS
- ◆ AGED 14 HOURS

CLOSED SYMBOLS INDICATE FOUNDRY A (0.59% MG)
OPEN SYMBOLS INDICATE FOUNDRY B (0.52% MG)

BROKEN LINE INDICATES THE AVERAGE OF ALL TESTS

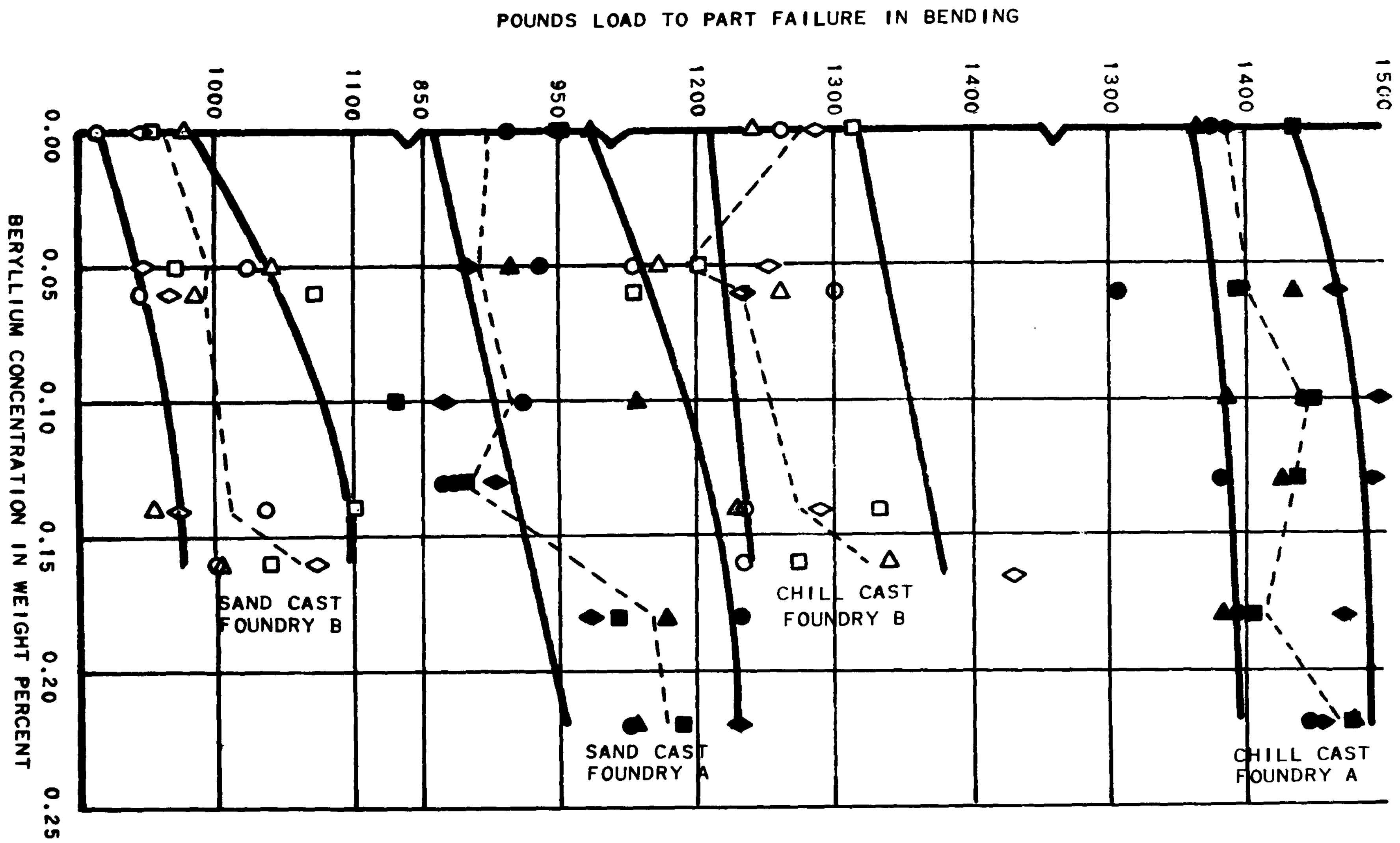


FIGURE 8

EFFECT OF BERYLLIUM CONCENTRATION ON THE PART STRENGTH OF 356-T6
TYPE ALUMINUM ALLOYS
(PARTS AGED AT 350° F)

● AGED 2 HOURS
◀ AGED 3 HOURS
■ AGED 5 HOURS
◆ AGED 10 HOURS

CLOSED SYMBOLS INDICATE FOUNDRY A (0.59% MG)
OPEN SYMBOLS INDICATE FOUNDRY B (0.52% MG)

BROKEN LINE INDICATES THE AVERAGE OF ALL TESTS

FIGURE 9

EFFECT OF BERYLLIUM CONCENTRATION ON THE MECHANICAL PROPERTIES OF CHILL CAST 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 CONDITION AT 320°F (160°C)

Solid lines indicate data from Foundry A (aluminum chills, 0.59 Mg)
Broken lines indicate data from Foundry B (iron chills, 0.52% Mg)

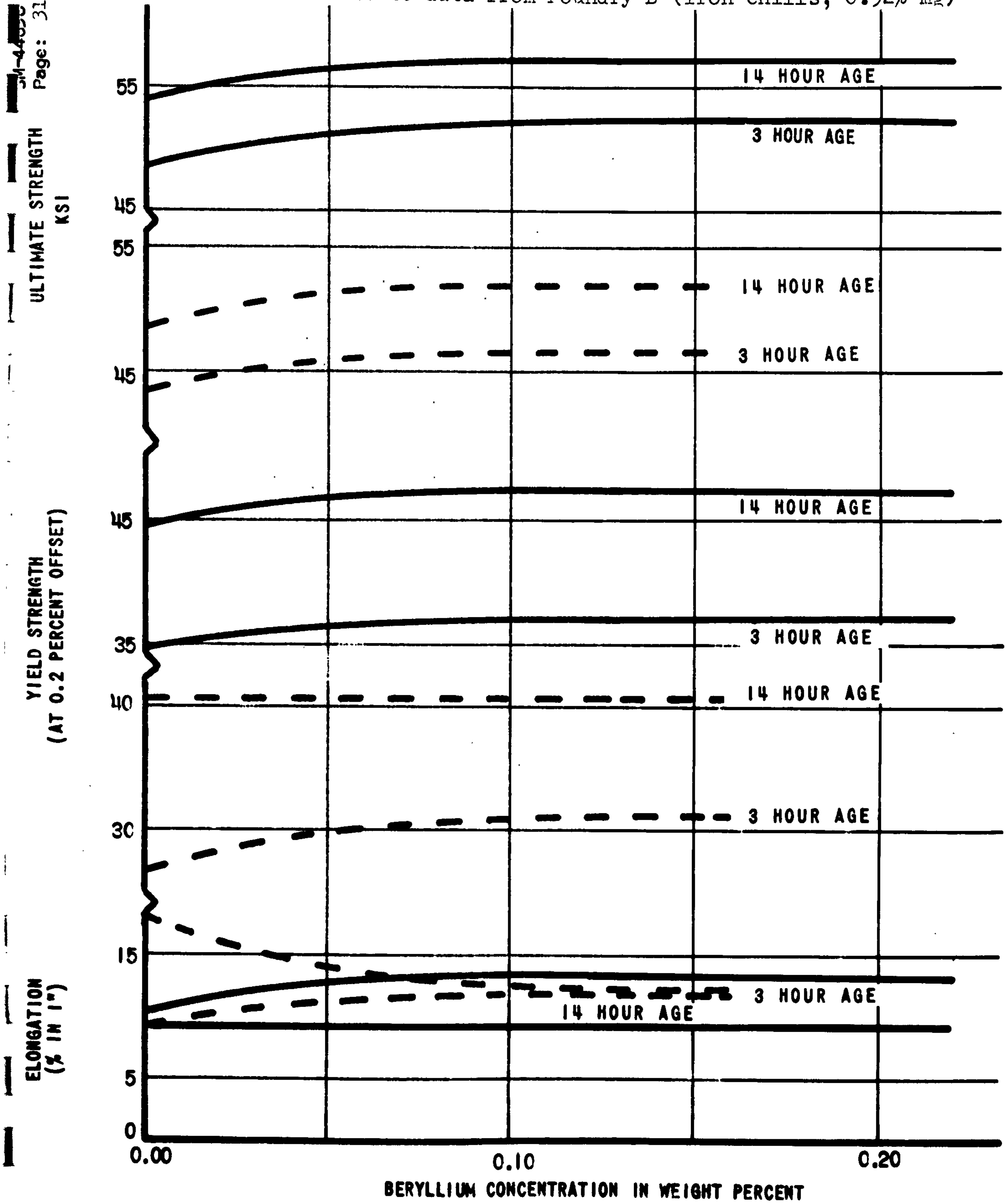


FIGURE 10 EFFECT OF BERYLLIUM CONCENTRATION ON THE MECHANICAL PROPERTIES OF CHILL CAST 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 CONDITION AT 350°F (177°C)

Solid lines indicate data from Foundry A (aluminum chills, 0.59% Mg)
Broken lines indicate data from Foundry B (iron chills, 0.52% Mg)

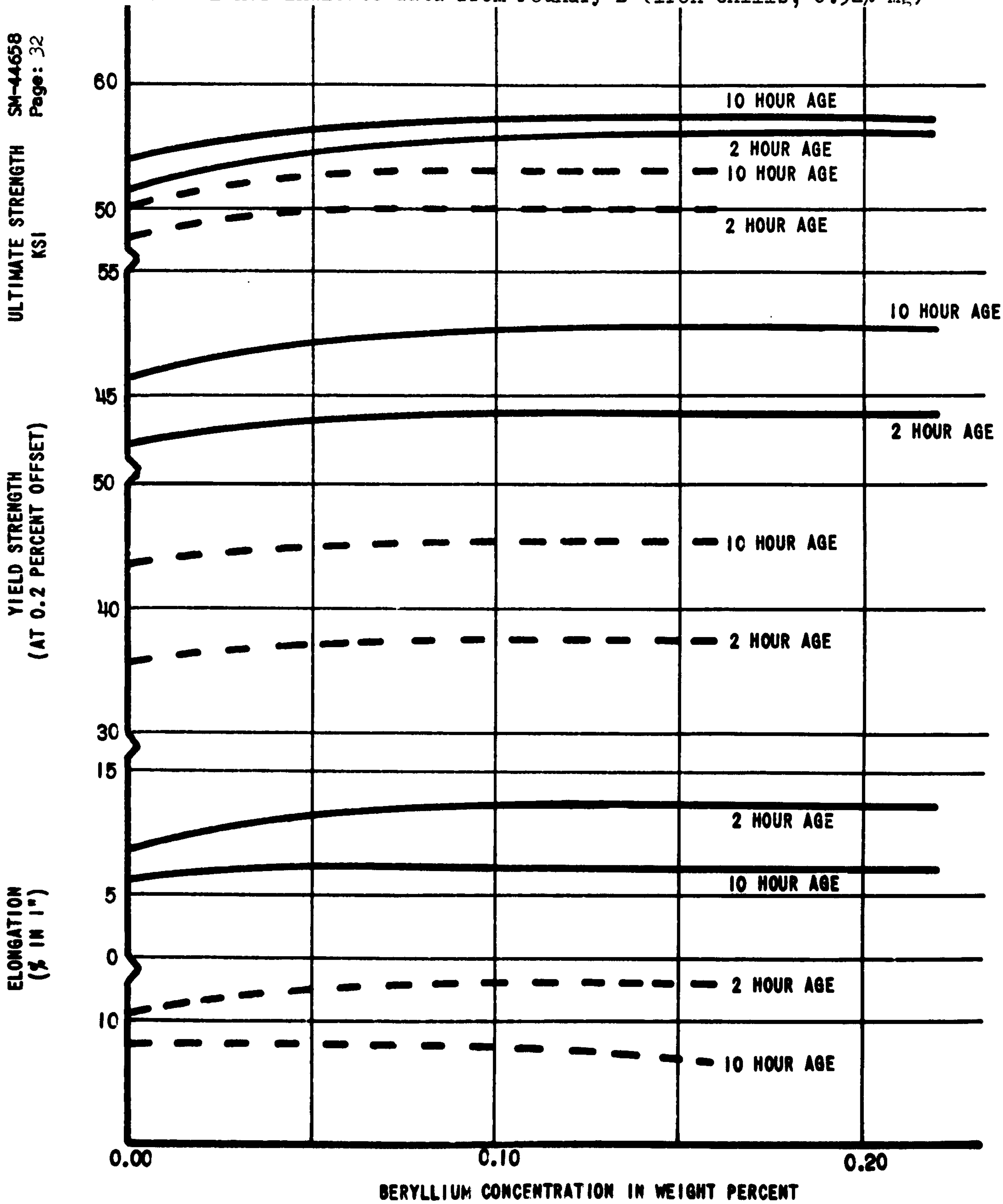


FIGURE 11

EFFECT OF BERYLLIUM CONCENTRATION ON THE MECHANICAL PROPERTIES OF SAND CAST 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 CONDITION AT 320°F (177°C)

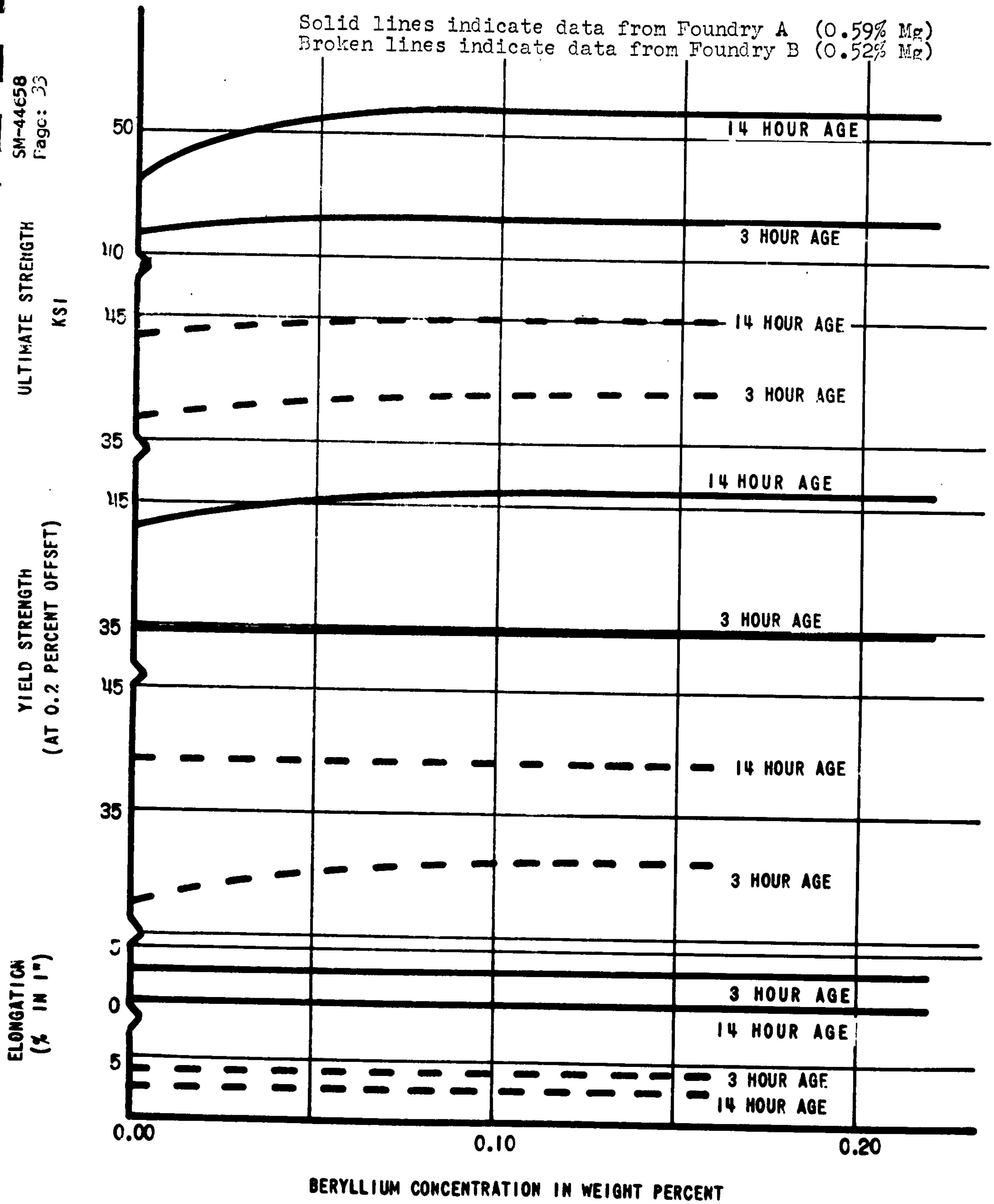


FIGURE 12

EFFECT OF BERYLLIUM CONCENTRATION ON THE MECHANICAL PROPERTIES OF SAND CAST 356-T6 TYPE ALUMINUM ALLOY AGED FROM THE T-4 CONDITION AT 350°F (177°C)

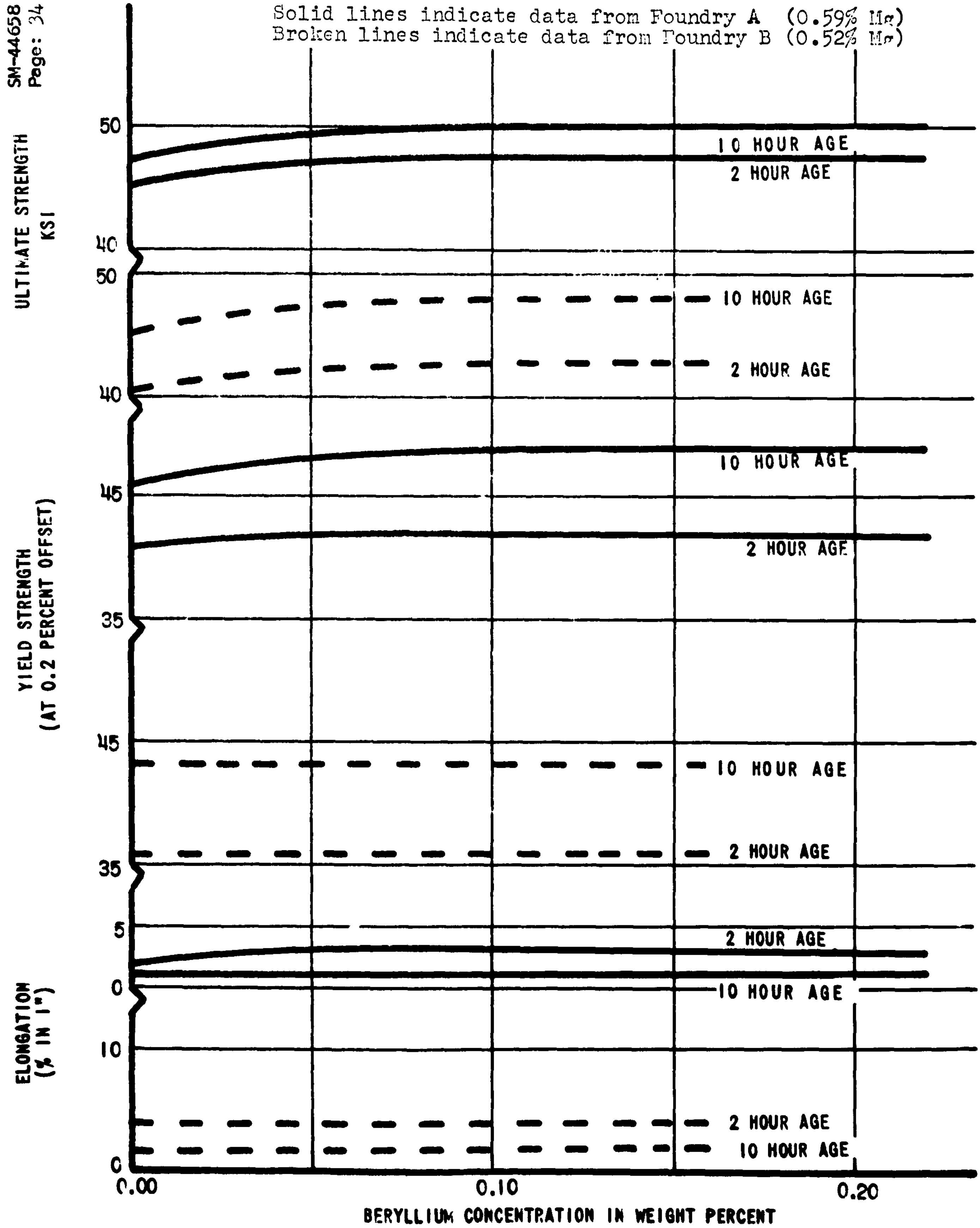


FIGURE 13

EFFECT OF SEVERAL AGING TIMES AND TEMPERATURES ON THE MECHANICAL PROPERTIES OF A 356 VARIANT – T6 ALUMINUM ALLOY

FOUNDRY A
COMPOSITION C (0.59% Mg – 0.00% Be)
SOLID LINES INDICATE RESULTS FROM CHILLED CASTINGS
BROKEN LINES INDICATE RESULTS FROM UNCHILLED CASTINGS

CHILL CAST ▲ SAND CAST ●

SYMBOLS PLOTTED ARE MEANS OF TWO TENSILE TESTS

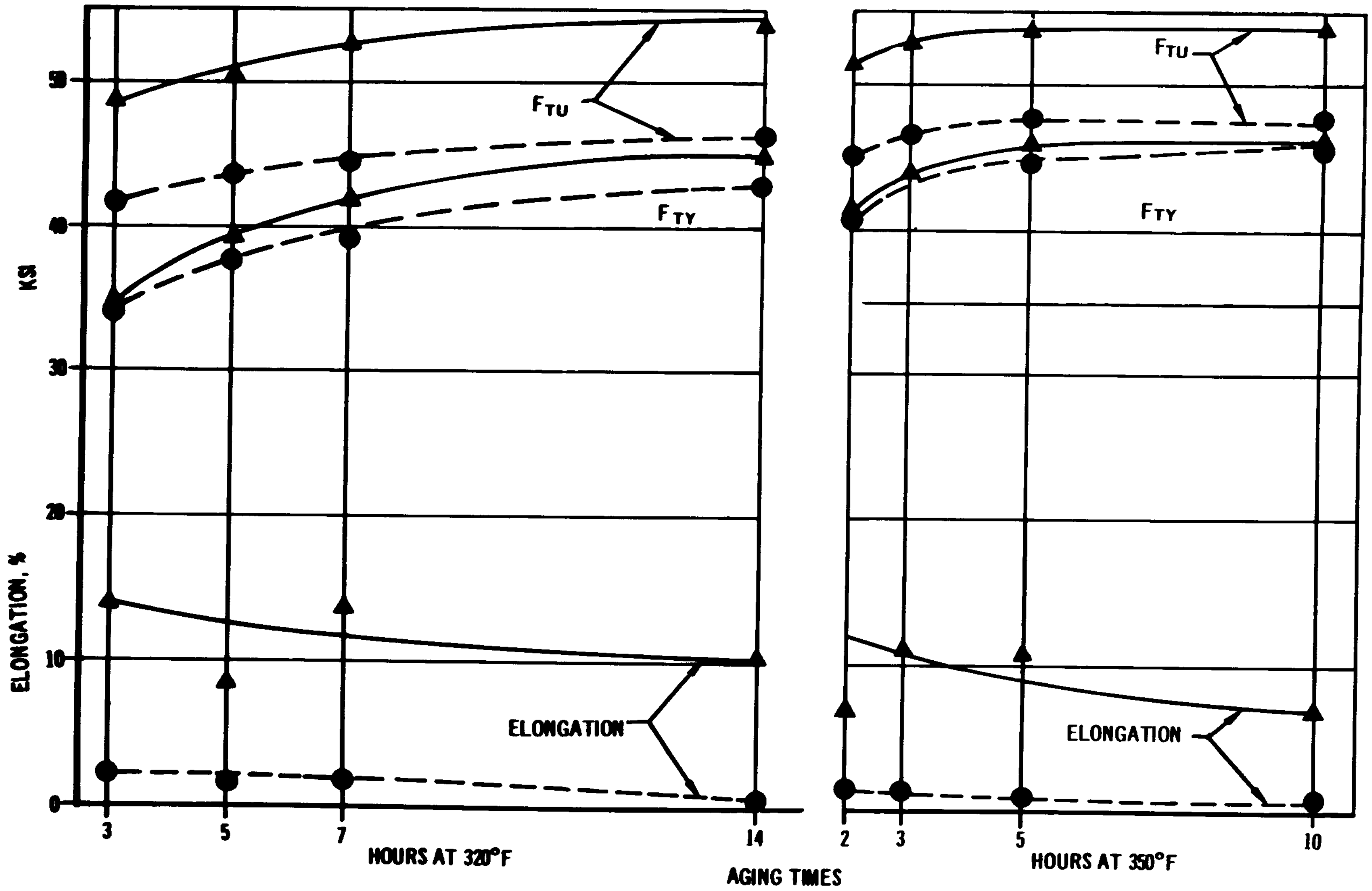


FIGURE 14

EFFECT OF SEVERAL AGING TIMES AND TEMPERATURES ON THE MECHANICAL PROPERTIES OF A 356 VARIANT – T6 ALUMINUM ALLOY

FOUNDRY A

COMPOSITION R (0.59% Mg – 0.10% Be)

CHILL CAST ▲ SAND CAST ●

SOLID LINE INDICATE RESULTS FROM CHILLED CASTINGS

BROKEN LINES INDICATE RESULTS FROM UNCHILLED CASTINGS

SYMBOLS PLOTTED ARE MEANS OF TWO TENSILE TESTS

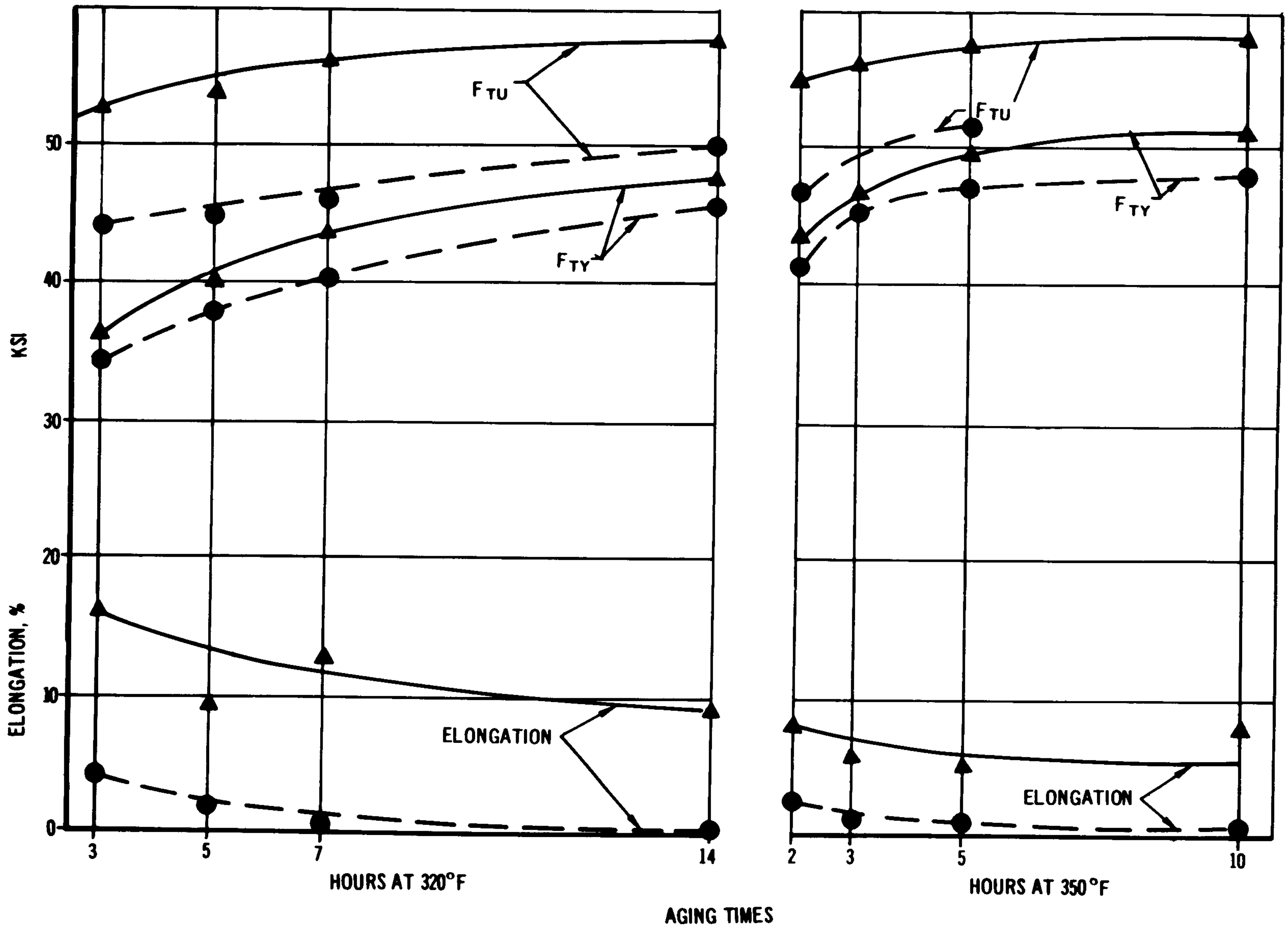


FIGURE 15 EFFECT OF SEVERAL AGING TIMES AND TEMPERATURES ON THE MECHANICAL PROPERTIES OF A 356 VARIANT – T6 ALUMINUM ALLOY

FOUNDRY A

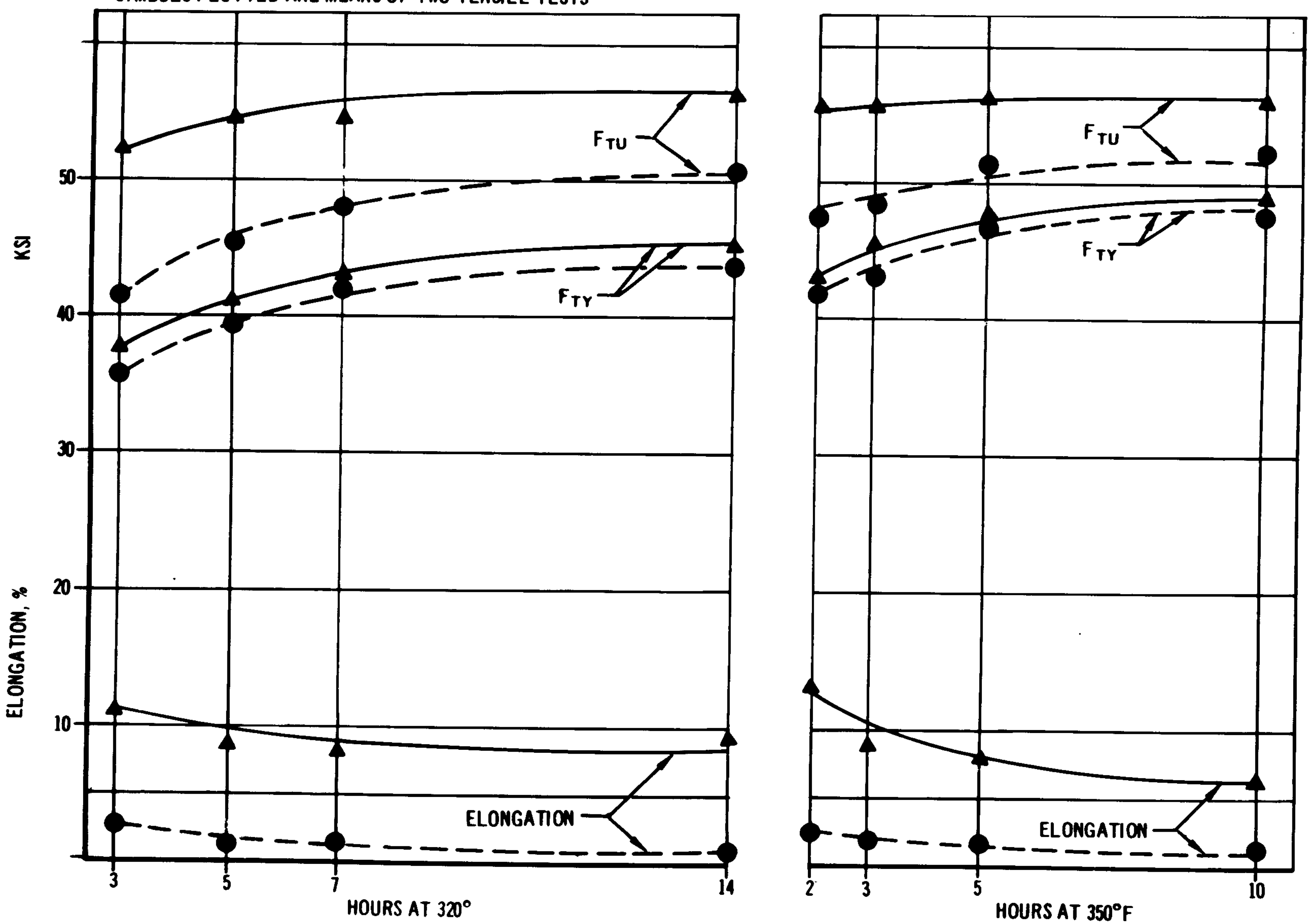
COMPOSITION U (0.60% Mg – 0.22% Be)

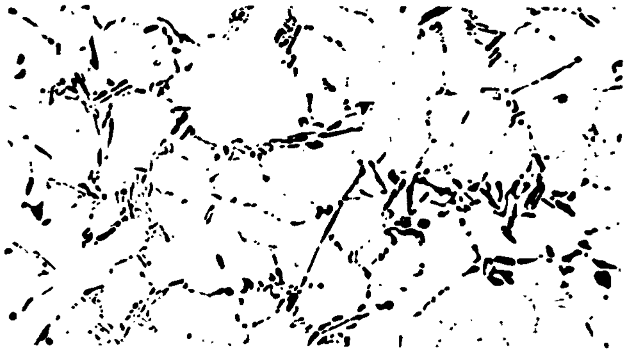
CHILL CAST ▲ SAND CAST ●

SOLID LINES INDICATE RESULTS FROM CHILLED CASTINGS

BROKEN LINES INDICATE RESULTS FROM UNCHILLED CASTINGS

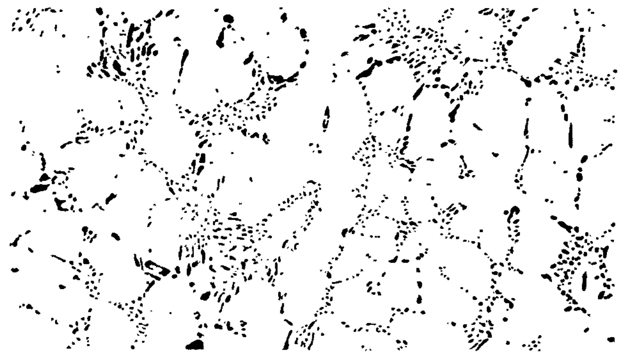
SYMBOLS PLOTTED ARE MEANS OF TWO TENSILE TESTS





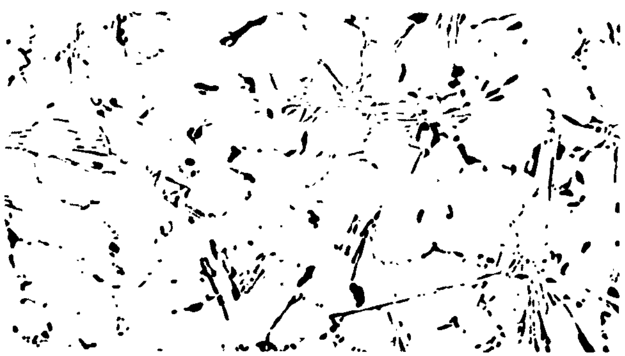
M16396

CAST BY FOUNDRY A
0.60% MG 0.00% BE



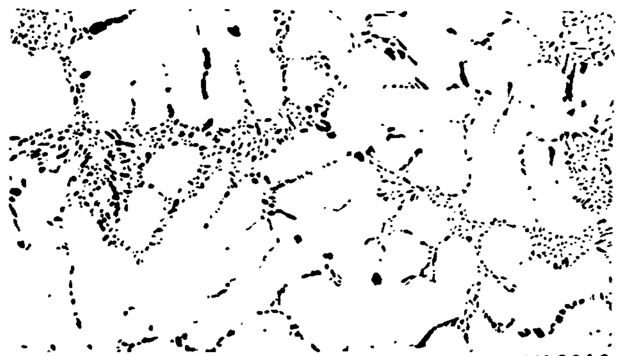
M16011

CAST BY FOUNDRY B
0.52% MG 0.00% BE



M16414

CAST BY FOUNDRY A
0.60% MG 0.22% BE



M16019

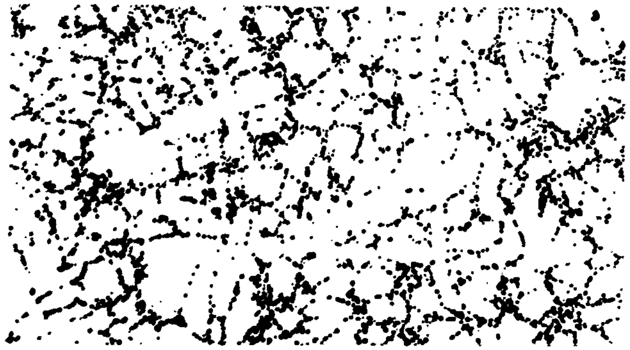
CAST BY FOUNDRY B
0.52% MG 0.16% BE

FIGURE 16

SAND CAST 356-T6 TYPE ALUMINUM ALLOY

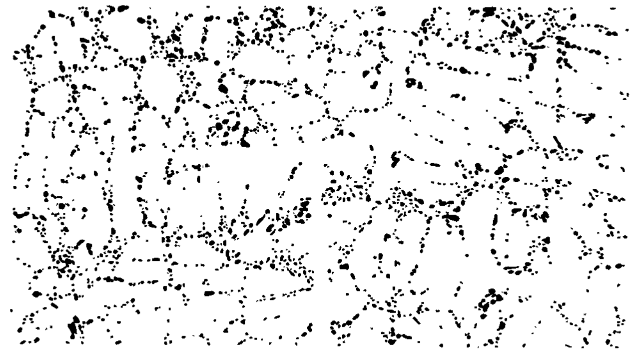
ALL PHOTOMICROGRAPHS 100X AND UNETCHED

AGED 3 HOURS AT 350°F (177°C)



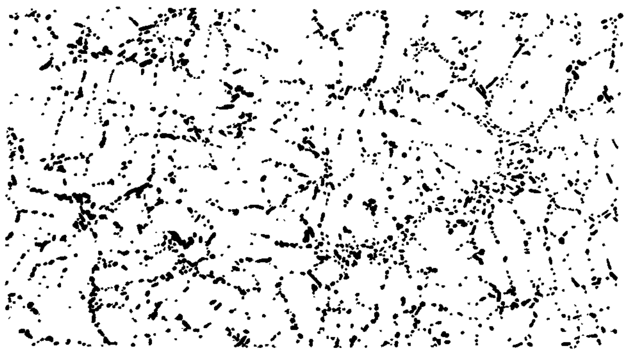
M16395

CAST USING ALUMINUM CHILLS BY FOUNDRY A
C.60% MG 0.00% BE



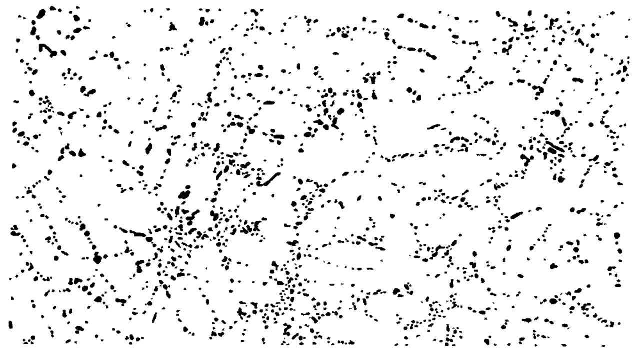
M16014

CAST USING IRON CHILLS BY FOUNDRY B
0.52% MG 0.00% BE



M16413

CAST USING ALUMINUM CHILLS BY FOUNDRY A
0.60% MG 0.22% BE



M16018

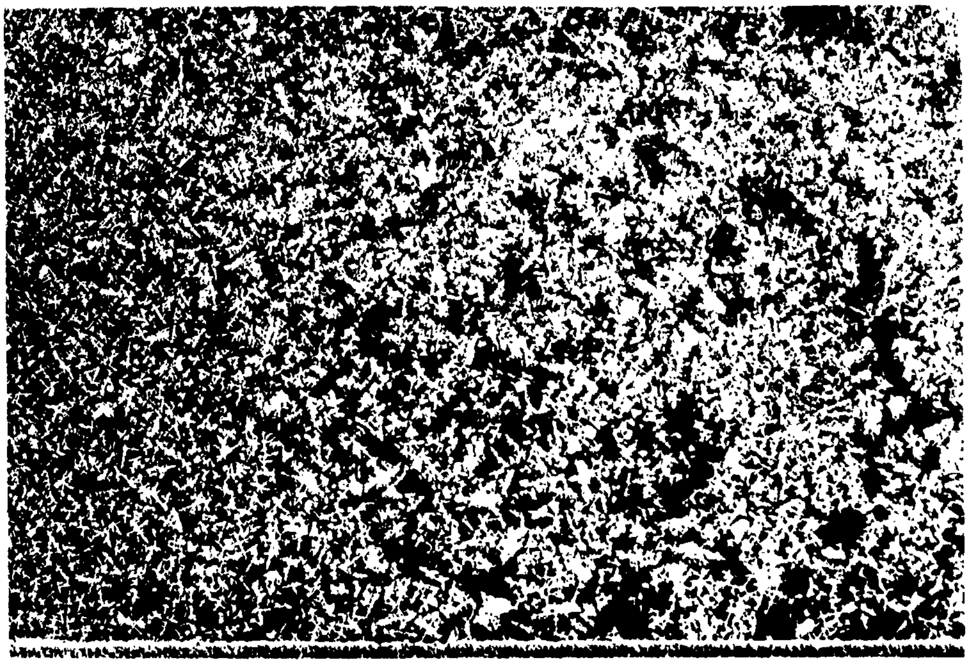
CAST USING IRON CHILLS BY FOUNDRY B
0.52% MG 0.16% BE

FIGURE 17

PERMANENT MOLD CAST 356-T6 TYPE ALUMINUM ALLOY

ALL PHOTOMICROGRAPHS 100X AND UNETCHED

AGED 3 HOURS AT 350°F (177°C)



MAGN. 7.5X FIGURE 18 M17522

CROSS SECTION OF "TEE" BAR ARM AT JUNCTURE WITH BASE
(SAND CAST IN 356-T6 ALUMINUM ALLOY)
ETCHANT: 5 PERCENT HF

MAGN. 7.5X FIGURE 19 M17521

CROSS SECTION OF "TEE" BAR ARM AT JUNCTURE WITH BASE
(CHILL CAST IN 356-T6 ALUMINUM ALLOY)
ETCHANT: 5 PERCENT HF

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